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Image segregation in strabismic amblyopia

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Abstract

Humans with naturally occurring amblyopia show deficits thought to involve mechanisms downstream of V1. These include excessive crowding, abnormal global image processing, spatial sampling and symmetry detection and undercounting. Several recent studies suggest that humans with naturally occurring amblyopia show deficits in global image segregation. The current experiments were designed to study figure–ground segregation in amblyopic observers with documented deficits in crowding, symmetry detection, spatial sampling and counting, using similar stimuli. Observers had to discriminate the orientation of a figure (an "E"-like pattern made up of 17 horizontal Gabor patches), embedded in a 7×7 array of Gabor patches. When the 32 "background" patches are vertical, the "E" pops-out, due to segregation by orientation and performance is perfect; however, if the background patches are all, or mostly horizontal, the "E" is camouflaged, and performance is random. Using a method of constant stimuli, we varied the number of "background" patches that were vertical and measured the probability of correct discrimination of the global orientation of the E (up/down/left/right). Surprisingly, amblyopes who showed strong crowding and deficits in symmetry detection and counting, perform normally or very nearly so in this segregation task. I therefore conclude that these deficits are not a consequence of abnormal segregation of figure from background.

Keywords: Amblyopia; Figure–ground segregation; Psychophysics; Form-perception

1. Introduction

Amblyopia is a developmental disorder of spatial vision usually associated with the presence of strabismus, anisometropia or form deprivation early in life (Ciuffreda, Levi, & Selenow, 1991; McKee, Levi, & Movshon, 2003). A longstanding question is the site of damage in amblyopia. While the earliest functional physiological abnormalities appear in cortical area V1 (for recent reviews see Barrett, Bradley, & McGraw, 2004; Kiorpes, 2006; Levi, 2006), several studies have also reported deficits in other areas (Barnes, Hess, Dumoulin, Achtman, & Pike, 2001); in V2 but not in V1 (Imamura et al., 1997); in occipitotemporal cortex (Lerner et al., 2003). Muckli et al. (2006) provide the most complete picture to date, showing that the responses of the amblyopic eye are progressively reduced in higher areas (V3a/VP; V4/V8 and LOC) and suggest that transmission of activity from the amblyopic eye is increasingly impaired as it is relayed to higher processing levels.

A number of recent psychophysical studies are consistent with the idea that the abnormalities in V1 are amplified in V2 and possibly beyond. These studies show losses in second-order detection (Mansouri, Allen, & Hess, 2005; Wong & Levi, 2005; Wong, Levi, & McGraw, 2001, 2005) global form and motion processing (Levi, Yu, Kuai, & Rislove, 2007; Mansouri et al., 2005; Mansouri & Hess, 2006; Simmers & Bex, 2004; Simmers, Ledgeway, & Hess, 2005; Simmers, Ledgeway, Hess, & McGraw, 2003), complex motion detection (Simmers, Ledgeway, Mansouri, Hutchinson, & Hess, 2006), symmetry detection (Levi & Saarinen, 2004), spatial sampling (Levi, Klein, & Sharma, 1999) excessive crowding (e.g., Levi, Hariharan, & Klein, 2002) and counting (Sharma, Levi, & Klein, 2000 – discussed below).

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When asked to count briefly presented stimuli, normal observers perform veridically. In contrast, strabismic amblyopes systematically undercount the number of features (Sharma et al., 2000). Moreover, amblyopes also undercount missing features ("holes" in a uniform texture of patches) and "different features" (e.g., horizontal patches amongst vertical). A low level deficit (e.g., reduced visibility) would predict overcounting of missing features (amblyopes would see fewer patches and therefore report more holes), so Sharma et al. concluded that there are likely to be high-level deficits in the amblyopic cortex, and that undercounting in amblyopia may reflect a limit in the ability to select and attend to individual features amongst other features. On the other hand, a recent study (Levi & Tripathy, 2006) showed that amblyopes are able to identify deviations in multiple trajectories with normal or near normal accuracy. Since this multiple object tracking task presumably also involves selection and attention, it raises the question of whether the counting deficit, as well as deficits in spatial sampling, global image processing (segregation and integration), symmetry detection and crowding might be a result of low or mid-level deficits rather than the high-level deficit suggested by Sharma et al. (2000).

While Sharma et al. considered a number of possibilities (reduced visibility, crowding, internal jitter), their results do not necessarily exclude the possibility of a deficit in image segregation. For example, if amblyopes are unable to segregate the signal (e.g., horizontal patches) from the background (vertical patches) they will likely undercount the "different features" in a texture of patches. Similarly, if the amblyopic visual system "fills-in" the holes in a uniform texture of patches, but cannot segregate the filled in holes from the patches, they would undercount. Similarly, an inability to segregate figure (target) from background (flanks) could result in excessive crowding and abnormalities in symmetry detection. Could a deficit in figure–ground segregation account for the amblyopes' inability to count accurately, detect symmetry and for their excessive crowding?

Amblyopic humans (Chandna, Pennefather, Kovacs, & Norcia, 2001; Hess, McIlhagga, & Field, 1997, 1999; Kovacs, Polat, Pennefather, Chandna, & Norcia, 2000; Levi & Sharma, 1998; Levi et al., 2007; Mussap & Levi, 1999, 2000) and monkeys (Kozma & Kiorpes, 2003) show difficulties in detecting contours in noise, as well as abnormalities in processing of global orientation and global motion in noise (Simmers et al., 2003, 2005; Simmers & Bex, 2004), and several studies suggest that this may be a result of abnormal segregation (Mansouri et al., 2005). Indeed, a recent study (Mansouri & Hess, 2006) places the blame squarely on processes involved in image segregation. The purpose of the experiment described here was to study figure–ground segregation in amblyopic observers with documented deficits in crowding, symmetry detection, spatial sampling and counting, using stimuli similar to those used in the experiments described above.

2. Methods

2.1. Stimuli

In order to minimize uncertainty we used a well-defined figure, an "E"-like pattern made up of 17 horizontal Gabor patches. The figure always appeared in the same location, varying only in it's global orientation (up/down/left/right). Note that the local orientation of the Gabor carrier patches was always horizontal. The figure was embedded in a 7×7 array of equally spaced Gabor patches which were identical in spatial frequency and contrast, with the sinusoidal carrier for all target patches horizontal and in the same phase (sine phase). However, the 32 "background" patches (those not included in the E) could be either vertical or horizontal. If the background patches are all vertical, the "E" pops-out, due to segregation by orientation, and it is trivial to identify the orientation of the E.

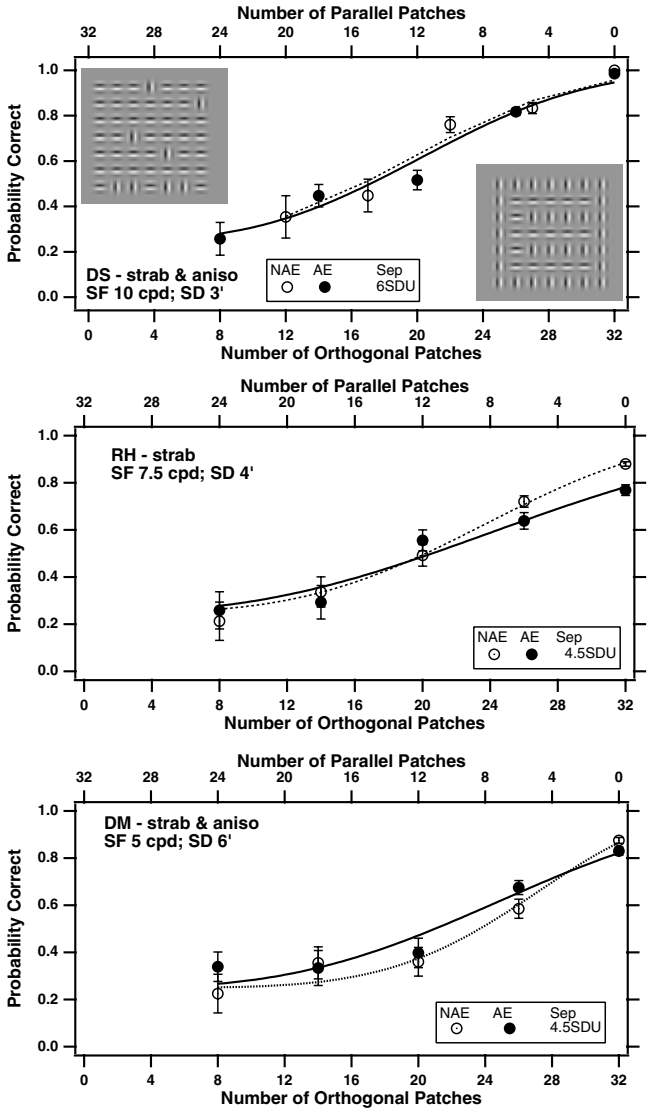

Fig. 1. Psychometric functions for discriminating the orientation of the figure (an "E"-like pattern shown in the insets). Each panel plots, for one amblyopic observer, the probability of correct responses as a function of the number of orthogonal background patches (lower abscissa) or the number of parallel patches (upper abscissa) out of 32. Open symbols are for the non-amblyopic eyes; solid symbols, amblyopic eyes. The lines show the Weibull functions fit to the data. Error bars are standard errors from the binomial distribution.

Table 1
Visual characteristics of amblyopic observers

Observer	Age	Sex	Eye	Rx.	Acuity[a]	Fixation[b]	Strabismus
Strabismic							
RH	32	M	O.D.	$-1.00/-0.50\times170$	20/15	Central	Constant microtropia
			O.S.	$-1.50/-1.50\times10$	20/59	Unsteady	l. et., 2^{Δ}
Strab & aniso							
DS	26	M	O.D.	+2.25 DS	20/40	2° nasal	Constant r. et., 8^{Δ}
			O.S.	+0.50 DS	20/20	Central	
DM	40	F	O.D.	$-0.50/-0.25\times92$	20/20	Central	Constant microtropia
			O.S.	$+2.50/-1.0\times160$	20/80	0.50° nasal	l. xt., 3^{Δ}

[a] 75% correct on Davidson–Eskridge charts.
[b] Fixation determined with haidinger's brushes and visuoscopy.

However, if the background patches are all, or mostly horizontal, the "E" is camouflaged, and performance is random (examples of these two extreme conditions are shown as insets in Fig. 1). Note that this 7×7 array is similar to the array used by Sharma et al. (2000) in counting both different features and holes.

We used the "E"-like pattern as the figure because it is well defined and very familiar, and the orientation judgment is simple (and frequently used as a clinical test). Importantly we have used this pattern in several experiments in the same observers in order to investigate internal noise and sampling (Levi et al., 1999), and crowding (Levi et al., 2002). We used Gabor patches for both figure and ground because they are limited in their spatial frequency bandwidth (1.1 octave or 0.5 cycles/standard deviation Levi & Klein, 1992). The use of band-limited stimuli makes it unlikely that differences between normal and amblyopic eyes can be explained on the basis of shifts toward lower spatial frequency linear first stage filters when viewing with the amblyopic eye (Levi, Waugh, & Beard, 1994). The patch spatial frequency (SF) and standard deviation (SD) were 10 cycles per degree (cpd) and 3′ for DS, 7.5 cpd/4′ for RH and 5 cpd/6′ for DM. For the amblyopes these spatial frequencies are scaled in proportion to the observer's acuity and were chosen to ensure that the stimulus was at least a factor of two below the cutoff spatial frequency for identifying the orientation of the E-like pattern (Levi et al., 1999) and the individual patches were well above their detection threshold. Note that the stimuli for all three conditions were identical on the screen, and the SF/SD were varied by changing the observers' viewing distance. Importantly, these three observers show excessive crowding, require more spatial samples, and undercount with similar stimulus parameters. The two normal observers were tested at several viewing distances. Viewing distance had no significant or systematic effect in the normal observers, and their results are combined across viewing distances. The stimuli had a contrast of 100% and were displayed on either a Mitsubishi Diamond Scan 20H monitor via a Cambridge Research Systems VSG 2 graphics card. The monitor frame rate was 72 Hz (non-interlaced) and the mean luminance of the display area was 56 cd/m^2.

2.2. Task

The observers' task was to judge the orientation of the "E"-like figure following each brief (200 ms) presentation. Using a method of constant stimuli, we varied the number of "background" patches that were vertical and measured the probability of correct discrimination of the global orientation of the E. The resulting psychometric functions were fit with a Weibull function in order to estimate threshold for identifying the orientation of the target. This figure–ground segregation threshold estimate, corresponding to the number of orthogonal (vertical) background patches resulting in 72.4% correct performance ($d'\approx1.6$), was based on 100 trials. The figure–ground segregation thresholds presented in the Results section are the weighted means of at least four individual threshold estimates. From run to run we varied the interpatch separation (3, 4.5 or 6 times the standard deviation) in order to assess the role of crowding.

2.3. Observers

Two normal observers (the author and an observer naïve as to the purpose of the experiments, ages 52 and 23, respectively) and three observers with strabismic amblyopia (one with pure strabismus, and two with both strabismus and anisometropia) participated in our experiments (Table 1). All were highly experienced in making psychophysical judgments and all were given practice on our tasks prior to data collection. In particular, we chose these three observers because each showed marked abnormalities in previous experiments using similar stimuli – in particular, in spatial sampling (Levi et al., 1999), crowding (Levi et al., 2002), symmetry detection (Levi & Saarinen, 2004) and counting (Hariharan, Tran, Levi, & Klein, 2002; Sharma et al., 2000).

3. Results

We asked observers to discriminate the orientation of an "E"-like pattern (up/down/left/right) made up of 17 horizontal Gabor patches, embedded in a 7×7 array of Gabor patches. When all 32 "background" patches are vertical, the "E" pops-out, due to segmentation by orientation (Fig. 1 top panel right inset) and performance is near perfect; however, if the background patches are all horizontal, the "E" is camouflaged, and performance is random (close to the 0.25 probability of guessing). Using a method of constant stimuli, we varied the number of "background" patches that were vertical (Fig. 1 top left inset shows 8 of the 32 background patches vertical) and measured the probability of correct discrimination. Fig. 1 shows sample psychometric functions for each eye (open symbols non-amblyopic eyes; solid amblyopic) of the three amblyopic observers. Note the surprising similarity between the psychometric functions of the two eyes of each observer. Indeed, the slopes (beta) of the Weibull functions were closely similar in the normal (3.57 ± 0.6), non-amblyopic (3.56 ± 0.6) and amblyopic (3.1 ± 0.4) eyes.

Fig. 2 (top panel) summarizes our results by plotting the threshold number of orthogonal background patches required for 72.4% correct identification of the orientation of the "E"-like pattern at each of the three inter-patch separations (specified in multiples of the patch standard deviation). Normal control observers required on average $\approx24.2\pm1.9$ (95% confidence interval) patches (shown by the gray dotted line and error bars), similar to both the non-amblyopic (26.8 ± 1.3 – black dotted line) and

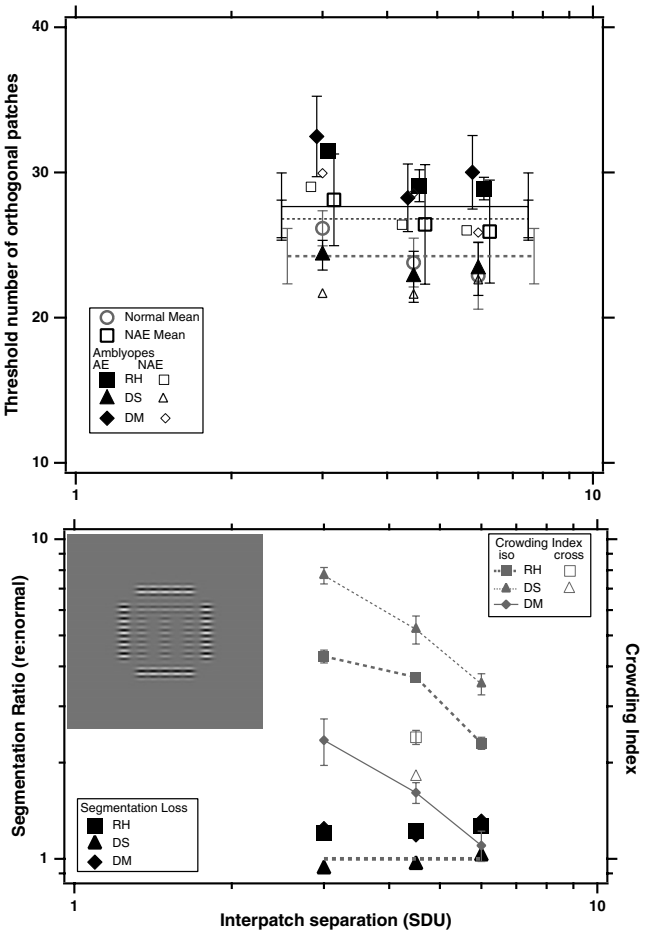

Fig. 2. *Top*. The threshold number of orthogonal background patches out of 32 required to correctly identify the orientation of the "E"-like pattern as a function of the inter-patch separation (in multiples of the patch standard deviation). Open symbols are for the non-amblyopic (squares) and normal control eyes; solid symbols, amblyopic eyes (circles). Solid symbols are the amblyopic eyes. The lines show the mean data (averaged across separations) for the normal (gray dotted) non-amblyopic (black dotted) and amblyopic (solid) eyes. Error bars are the 95% confidence interval. *Bottom*. Elevation of segmentation thresholds (left ordinate – solid black symbols) and crowding index (right ordinate – gray symbols) for each of the amblyopic eyes. The inset shows the E-like pattern and flankers used in the crowding experiment. Solid gray symbols are with iso-oriented target and flanks; open gray symbols are with cross-oriented target and flanks. The dotted horizontal line at a ratio of one indicates no elevation of segregation thresholds and no crowding. The segmentation thresholds do not depend on inter-patch separation while the crowding index does.

amblyopic (27.6 ± 2.3) eyes, with little effect of inter-patch separation. Although the amblyopic eyes of both DM and RH have slightly higher thresholds than the normal mean (≈14%) and the mean of the non-amblyopic eyes (≈3%), these difference are small compared to the marked abnormalities each of the amblyopic observers demonstrate in crowding (Levi et al., 2002); symmetry detection (Levi & Saarinen, 2004) and counting (Hariharan et al., 2002 & Sharma et al., 2000). For example, observer DS shows a factor of ≈5 threshold elevation in a crowding experiment using a similar "E"-like target, with iso-oriented flankers at a separation of 4.5 SDU and about a 2-fold threshold elevation with orthogonal flankers (Fig. 2 lower panel; Levi et al., 2002); an approximately 66% increase in symmetry detection thresholds, and a substantial degree of undercounting. On the other hand his segregation thresholds are equal to or lower than the normal controls, so we conclude that difficulties in image segregation are unlikely to explain the poor performance on these other tasks (crowding, symmetry detection and counting). Qualitatively similar results are seen for the other observers (Fig. 2 lower panel).

The lower panel of Fig. 2 (left ordinate) shows the elevation of segmentation thresholds for each of the amblyopic eyes (i.e., the ratio relative to the normal mean). The dotted horizontal line at a ratio of one indicates no loss in performance. The right ordinate shows the crowding index (the elevation of contrast threshold for discriminating the orientation of the E-like pattern shown in the inset due to flanks). A crowding index of one indicates no crowding. Although the threshold elevations in the two tasks may not be strictly quantitatively comparable, it is clear that they differ both in degree and qualitatively. The segmentation thresholds do not depend on inter-patch separation while the crowding index does. Moreover, excessive crowding occurs even for orthogonal flankers (cross – open symbols).

4. Discussion

Our main result is that strabismic amblyopes with well-documented deficits in symmetry detection (Levi & Saarinen, 2004), crowding (Levi et al., 2002), sampling (Levi et al., 1999) and counting (Sharma et al., 2000) using similar stimuli perform normally or very nearly so in this segregation task. Our results are consistent with earlier work using a rather different task (Mussap & Levi, 1999) in showing that strabismic amblyopes are capable of normal orientation-based texture segmentation. However, they may appear to be, on the surface, at odds with those of Mansouri and Hess (2006). Specifically, Mansouri and Hess (2006) presented arrays of randomly positioned Gabor patches that moved (or oriented) in a direction chosen from a Gaussian distribution with a variable bandwidth and a mean of 90°. The observers' task was to judge whether the mean direction (or orientation) of the array was to the left or right of vertical. Mansouri & Hess varied both the standard deviation of the "parent" distribution and the amount of "pedestal" noise, that is they varied the percentage of elements whose directions (orientations) were chosen at random from a uniform distribution, thus creating a noise pedestal. Using an equivalent noise model, they suggest that amblyopic eyes can integrate form and motion information normally; however, adding pedestal noise perturbs performance. Thus they concluded that the global processing deficit is one involving deficient signal segregation. The Mansouri & Hess experiments are inherently noisy since the observers' judgments are about

the statistical properties of two noisy distributions, and involve a judgment relative to an inferred standard (90°), they therefore contain a large degree of uncertainty. In contrast, our stimuli contained a well-defined figure, and both the figure and background elements were in known (and fixed) locations. Under these conditions (which are similar to the conditions used in our crowding, symmetry and counting experiments), segregation based on orientation appears to be normal or nearly so in the amblyopic visual system. Note that in the experiments of Mussap and Levi (1999) there was also little uncertainty because the task involved detecting the orientation of a texture edge.

We are not arguing that amblyopes never show deficits in image segregation. Indeed, a recent study (Levi et al., 2007) shows that even after compensating for the well known early deficits in visibility and positional uncertainty, humans with naturally occurring amblyopia (particularly those lacking binocular vision) show modest deficits in global contour processing, and that, at least in some amblyopes, abnormal image segregation may be implicated. Specifically, similar to the Mansouri and Hess results, Levi et al. (2007) found that some observers demonstrate normal or near normal form perception in the absence of noise, but significant deficits in noise, which is not improved by increasing the number of target patches (i.e., if the amblyopic eye is unable to segregate figure from the background, increasing the number of target will not help). These results suggest that amblyopes may show both integration and segregation deficits in global image processing, even after compensating for many of the well known for low-level deficits. While such deficits have been suggested to occur beyond the initial filtering stage (Kiorpes, 2006), recent work (e.g., Kourtzi, Tolias, Altmann, Augath, & Logothetis, 2003; Li, Piech, & Gilbert, 2006) make it clear that the deficits might occur as early as V1 (via lateral connections and/or feedback). What the present study shows is that these deficits are unlikely to contribute to the excessive crowding, abnormal symmetry detection, undersampling and undercounting evident in our observers.

Interestingly, patients with parietal lesions, like our amblyopes, also show deficits in symmetry judgments but preserved figure–ground segregation (Driver, Baylis, & Rafal, 1992). Driver et al. suggest that in these patients, information which is neglected and unavailable to higher levels of visual processing can be processed normally by earlier stages in the visual system, where figure–ground segregation takes place. Driver et al. argue for a two-stage account: a preattentive segregation stage providing "candidate objects to a subsequent attentional stage". In parietal lesions, the first stage remains intact while the latter stage is impaired.

The present results, showing normal or nearly normal image segregation in amblyopes who show marked impairments in crowding, symmetry detection, undersampling and undercounting under similar stimulus conditions, suggest a similar explanation – a normal or nearly normal image segregation stage, and further impairment downstream. Indeed, it has been previously suggested that amblyopia might involve deficits downstream from V1 (e.g., in parietal lobe- McKee et al., 2003; Sharma et al., 2000; Simmers et al., 2003, 2005, 2006; Wong et al., 2001, Wong, Levi, & McGraw, 2005), in addition to the well-documented deficits in V1 in amblyopia associated with abnormal binocular interaction (Smith et al., 1997). The present results are consistent with this notion.

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